Four channel DFB laser array with integrated combiner for 1.55 $\mu$m CWDM systems by MOVPE selective area growth

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Abstract: Monolithically integrated four-channel distributed feedback (DFB) laser array has been fabricated by metal organic vapor phase epitaxy (MOVPE) selective area growth for 1.55 $\mu$m coarse-wavelength division multiplexing (CWDM) systems. Wide-stripe MOVPE selective area growth and electron-beam lithography are used to obtain wide CWDM channel spacing of 20 nm. Optical outputs from the simultaneously biased four DFB lasers are combined via an integrated multimode interference coupler before coupled to a single mode fiber. Compared to hybrid integration of discrete lasers, monolithic integration of laser array on a single substrate simplifies optical alignment and packaging.

Keywords: distributed feedback laser, laser array, coarse wavelength division multiplexing (CWDM), MOVPE selective area growth

Classification: Photonics devices, circuits, and systems

References
1 Introduction

With increasing network traffic in metropolitan and access networks, carriers are seeking cost-effective solutions to meet their transport needs. Coarse wavelength division multiplexing (CWDM) systems offer lower power dissipation, smaller size, and lower cost compared to dense wavelength division multiplexing (DWDM) systems. Monolithically integrated distributed feedback (DFB) laser diode arrays with simultaneous multichannel operations are key device for CWDM systems. Compared to hybrid integrated laser array modules consisting of discrete DFB lasers, well-designed monolithically integrated DFB laser arrays can potentially lower system cost by simplifying optical alignment and packaging process. Although lower fabrication yield of monolithic DFB laser arrays has been cited as one of the main issues, CWDM light sources have much wider channel spacing (20 nm) than their DWDM counterparts which results in looser fabrication tolerance and higher fabrication yield.

| Table I. Recent Work on Multi-λ Monolithically Integrated DFB Laser Array |
|---------------------|---|-----------------|---|---|
| Structure.          | Method | Ch# /array | Range, Spacing [nm] | Year | Ref |
| Array+Coupler+SOA   | EB litho | 8 | 1546-1560, 2 | 1997 | 1 |
| Array+Power Monitor | EB litho | 4 | 1554-1560, 2 | 1999 | 2 |
| Multiple Arrays (six) | NS-SAG+EB | 8 | 15-20, 2.0-2.7 | 2003 | 3 |
| Array+Coupler+SOA   | WS-SAG+EB | 4 | 1543-1552, 2.4 | 2004 | 4 |
| Array               | NS-SAG+EB | 4 | 1291-1352, 20 | 2005 | 5 |
| Array+Coupler       | WS-SAG+EB | 4 | 1520-1580, 20 | This work | |

NS-SAG=Narrow-Stripe SAG, WS-SAG=Wide-Stripe SAG

A brief summary of DFB laser array research over the past decade is presented in Table I. In many of these works, the lasing wavelength is changed either by varying the grating pitch by electron-beam lithography [1], or by varying the waveguide effective refractive index by altering the width of the ridge waveguide for example [2]. However, the wide wavelength spacing of CWDM systems limit the number of channels than can be monolithically fabricated using advanced microarray-selective epitaxy,” IEEE Photon. Technol. Lett., vol. 16, no. 7, pp. 1619–1621, July 2004.


integrated on the same substrate since too large lasing wavelength detuning from the gain peak would result in Fabry-Perot mode lasing. Due to this reason, fabrication of integrated CWDM laser arrays requires special crystal growth methods to form multiple bandgap regions on the same substrate. Among these methods, metal organic vapor phase epitaxy (MOVPE) selective area growth (SAG) is particularly advantageous for CWDM laser array since a large number of bandgap regions can be formed in a single epitaxial growth. In order to determine the lasing wavelength, grating formation by e-beam lithography is suitable since gratings with different periods are to be formed on different, localized areas of the substrate.

Depending on the width of the SiO$_2$ mask opening, MOVPE SAG can be categorized into narrow-stripe (NS) and wide-stripe (WS) SAG with 1 to 2 $\mu$m and $> 5 \mu$m mask openings, respectively. Due to its self-aligned characteristics, narrow-stripe SAG is particularly attractive for fabricating buried-heterostructure DFB lasers. Tsuruoka et al. utilized narrow-stripe SAG to fabricate a four-channel AlInGaAs DFB laser array for 1.3 $\mu$m CWDM systems, where light output from each channel is coupled to a fiber array [3]. On the other hand, wide-stripe SAG offers greater flexibility for integration of passive and active regions, which allows integration of the laser array with a passive multi-mode interference (MMI) combiner/coupler; therefore the combined output can be coupled into a single mode fiber instead of into a fiber array. Utilizing wide-stripe SAG, Yashiki et al fabricated an integrated wavelength-selectable DFB laser array in which light output from only one of four DFB lasers with 2.4 nm wavelength spacing is coupled to a single mode fiber after passing through an MMI combiner [4]. However, for CWDM systems simultaneous lasing operation of all four DFB lasers is required. In this work, we utilized wide-stripe SAG to fabricate the first monolithically integrated DFB laser array with MMI coupler for 1.55 $\mu$m CWDM systems.

2 Principle of Selective Area Growth

Selective area growth on mask patterned semiconductor substrate is an attractive method for integrated photonics since active and passive waveguide layers in monolithically integrated devices can be formed simultaneously. This greatly simplifies the fabrication process and improves device/array yield. Since growth does not take place on the SiO$_2$ mask, group III species diffuse from above the mask to the SAG region, thus enhancing the growth rate in the SAG region. Thicker quantum wells due to enhanced growth rate, along with higher In content due to higher sticking coefficient of In relative to Ga, result in the peak shift in the SAG region towards longer wavelength. The amount of shift is determined by the ratio of mask width over mask opening, $W_m/G_m$. In wide-stripe SAG with $G_m > 5 \mu$m, the active and passive waveguides are formed on the masked and planar unmasked regions, respectively. Either buried heterostructure or ridge waveguide laser can be formed through mesa etching of the center region of the mask opening. In this work, $G_m$ is set to be 15 $\mu$m, while $W_m$ is 24 $\mu$m, 32 $\mu$m, 38 $\mu$m, 44 $\mu$m
Fig. 1. Topview of SAG region (top left) with SiO$_2$ in light color and grown layer in dark color. Cross section of the SAG region (top right). PL spectra from the SAG regions with different mask widths (bottom) for target peak wavelengths of 1530 nm (ch1), 1550 nm (ch2), 1570 nm (ch3), and 1590 nm (ch4), respectively. SEM micrographs and µ-PL spectra of the SAG regions are shown in Fig. 1. The peak wavelengths show good run-to-run reproducibility. The planar passive region for has peak wavelength of 1420 nm, hence the wavelength shift is 110 nm to 170 nm for ch1 and ch4, respectively.

3 Fabrication and Measurement

The fabrication process of the monolithically integrated CWDM DFB laser array consists of four main steps: 1) InGaAsP DFB grating formation by e-beam lithography and wet etching by saturated Br water:HBr:H$_2$O, 2) SiO$_2$ selective area growth mask patterning by lithography, 3) MOVPE selective area growth of InGaAsP multi-quantum well (MQW) core layers followed by growth of p-doped InP cladding and InGaAs cap layers, 4) and DFB laser waveguide fabrication using conventional laser diode fabrication process. As four different grating periods need to be defined at specific locations on the substrate, grating formation by e-beam lithography is clearly preferred for holographic lithography. SiO$_2$ is used as the grating mask during wet etching. MQW layer grown over grating parallel to [011] direction is found to have better crystalline quality than [011] direction due to the absence of (111)
facets. During temperature rise prior to growth, both As and P are supplied to preserve the InGaAsP grating shape. Moreover, reducing the growth rate of InP buffer layer to bury the grating has been found to result in better MQW crystalline quality. Selective wet etching of InGaAs and InP with $\text{H}_2\text{SO}_4$:$\text{H}_2\text{O}_2$:$\text{H}_2\text{O}$ and HCl solutions, respectively, is used to form the ridge waveguides. After waveguide formation, absorptive InGaAs contact layer on the passive waveguide region is removed by wet etching.

Fig. 2 (top) shows the fabricated monolithically integrated four-channel CWDM DFB laser array along with its dimensions. Separation between two adjacent lasers is set to be 250 $\mu$m. Although narrower separation is possible by utilizing a similar SAG technique described in [4], electrical/thermal crosstalk becomes an issue to be overcome. Main sources of optical losses are the inherent MMI splitter/combiner loss (6 dB) and passive region absorption losses due to absorption in the passive region and/or due to inevitable p-doping of the InP cladding in order to form the p-i-n laser structure. The MMI width is 30 $\mu$m to allow for sufficient waveguide separation at the MMI.
entrance to prevent coupling between adjacent waveguides. The MMI lengths for each wavelength are calculated using the formula for four-to-one symmetric MMI splitter/combiner as described in [6]:

$$L = \frac{1}{4} \left( \frac{n_r W^2}{\lambda_0} \right)$$

(1)

where $n_r$ is the waveguide effective refractive index, $W_e$ is equivalent MMI width including the slight penetration into the neighboring area of the waveguide, and $\lambda_0$ is the free-space wavelength. For a shallow-etched ridge waveguide structure, the calculated MMI lengths vary from 536 $\mu$m to 518 $\mu$m for 1530 nm and 1570 nm channel wavelengths, respectively; therefore a middle compromise value of 527 $\mu$m is chosen. Calculated 0.5 dB bandwidth tolerances are $\pm$28 $\mu$m and $\pm$0.8 $\mu$m for the MMI coupler length and width, respectively. As a 1-to-4 or 6 dB splitter, the guided modes at the four-arm port show roughly uniform near-field intensities at the designed MMI length as shown in Fig. 2 (middle left). The near-field intensity distribution was obtained using a Hamamatsu DV-3000 digital image processor. Fig. 2 (middle right) shows the topview of the wet-etched MMI coupler with a 45$^\circ$ tilt at the corners due to etching anisotropy. Compared to high index contrast high-mesa MMI coupler, low index contrast ridge MMI coupler has the advantages of looser fabrication tolerance and less back reflection from the etched MMI facets.

Simultaneous continuous wave (CW) lasing spectra of the four-wavelength DFB lasers from the same array are shown in Fig. 2 (bottom). The laser arrays are mounted on Cu chip carrier, whose temperature is maintained at 15°C by thermoelectric cooler. The cleaved facets are left to be as-cleaved without AR or HR coating. At a bias current of 100 mA injected to each laser, the lasing wavelengths are around 1521.2 nm, 1541.5 nm, 1563.9 nm, and 1580.6 nm; therefore the wavelength spacing corresponds to the CWDM spacing of 20 nm. Although the lasing wavelengths are 10 nm shorter than the target wavelengths, they can be shifted by fine adjusting the e-beam exposure conditions. At simultaneous operation, the side mode suppression ratio (SMSR) for each channel is approximately 30 dB, which can be improved by inserting a quarter wavelength shift at the middle of the laser cavity.

### 4 Conclusion

In this paper, we have showed how wide-stripe selective area growth and e-beam lithography can be utilized to fabricate integrated four-channel 1.55 $\mu$m DFB laser array for CWDM systems. Compared to other monolithic integration schemes, this method is superior in terms of simplicity and scalability, which is particularly advantageous for fabricating laser arrays with a large channel count, such as four or eight channels required for CWDM systems. In this work, Light outputs from four simultaneously biased DFB lasers with approximately 20 nm wavelength spacing are combined using an integrated MMI coupler before being coupled to a single mode fiber, which greatly simplifies optical alignment and reduces system size/packaging cost.
Higher fiber-coupled output power can be achieved by SAG integration with a wide-band semiconductor optical amplifier.

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